Institute of Paper Science and Technology
Atlanta, Georgia

IPST TECHNICAL PAPER SERIES

NUMBER 367

CHARACTERIZATION OF IN-PLANE FLOW IN PAPER

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DECEMBER, 1990

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Submitted for AIChE Chicago Annual Meeting
November 11-16, 1990

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CHARACTERIZATION OF IN-PLANE FLOW IN PAPER

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ABSTRACT

The importance of two-dimensional flows in paper is increasingly being recognized. An understanding of such flows has been limited in the past due to an absence of data about the lateral (in-plane) permeability of paper. Measurements of lateral and transverse permeability components in a variety of paper samples have now been made. This information about the anisotropic flow characteristics of paper indicates that simple models of flow in fibrous media are inadequate in describing paper. In particular, the in-plane permeability tends to be higher than simple models predict, with in-plane permeabilities ranging from 2-10 times as great as the corresponding z-direction component. The results of these measurements are consistent with recent data for in-plane permeability in textiles. Several practical implications are discussed.

INTRODUCTION

While flow normal to the plane of paper is of great importance in many papermaking processes, the in-plane flow of liquid through paper is receiving increasing attention. Significant in-plane flows of water during wet pressing can occur (1-4), and lateral penetration of coating colors can be important in blade coating processes (5). In the area of photography, excessive lateral penetration of developing fluids into the edge of the paper can ruin a photograph. In impulse drying, strong vapor pressure gradients in the machine direction may be a major cause of the delamination problem which can occur with some furnishes (6). All such flows are affected by the in-plane or lateral permeability of paper, a parameter which has been neglected in previous studies of paper permeability. While much has been published about the z-direction or transverse permeability of paper, measurements of the lateral permeability components and their relation to transverse permeability have not been available in the literature. For lack of better information, those who have dealt with two-dimensional flows in paper have thus tended to assume that the permeability of paper was uniform in all directions (1,7,8), even though paper is an obviously anisotropic material.

This lack of data is surprising, since similar measurements have been made in felts, textiles, rocks, and other porous materials. Experimental difficulties in constraining the flow to the plane of the paper, without permitting channeling along the surface of the sheet, seem to have hampered some previous efforts (see discussion in [9]).

Relevant work, however, has been done by Back (10), who examined in-plane capillary flows in paper. By observing the way in which a drop of fluid spreads out in a sheet of paper, information about anisotropy in the sheet can be obtained. He found that the capillary penetration velocity for most papers is 5-15% larger in the machine direction than in the cross-direction. However, capillary flow is affected by both the intrinsic Darcian permeability of the sheet as well as the directional pore size distribution. No quantitative conclusions about permeability can be safely deduced from such experiments unless detailed information about directional pore-size distributions is available.

While no published measurements in paper are known, Peterson (11) examined the two-dimensional permeability of thick, nylon fiber mats with fibers oriented in the horizontal plane. He found the lateral permeability was 25-30% higher than the transverse permeability. Mat porosities ranged from 0.84 to 0.97. While a thick nylon mat is not an accurate model of paper, the study provides an important reference point.

To explore basic issues about the anisotropic permeability of paper, a small project was launched at the Institute of Paper Science and Technology in 1987. Results from the first phase of the study have now been published by Lindsay (12), who measured the transverse, cross-direction, and machine-direction permeability components in several paper samples. In the few samples which were examined, the ratio of average lateral to transverse permeability ranged from roughly 2 to 4, which was much larger than predicted by simple models of flow over oriented cylindrical rods (13,14), but consistent with new data from Adams (15) for textiles, in which ratios of 2 to 5 were reported.

The ratio of machine-direction to cross-direction permeability was also obtained in several paper samples in the previous study (12), with values generally in the range of 1 to 2, and frequently in the range of 1.1 to 1.3. In a related study by Horstmann et al. at IPST (16), a new experimental method to characterize edge penetration in photographic papers was used to provide information on anisotropic in-plane permeability. Measurements in 5 similar samples of uncompressed photographic paper again showed MD-CD permeability ratios in the range of 1.1 to 1.3. Transverse permeability was not measured.

In this paper, we describe recent measurements of lateral and transverse permeability in paper using improved techniques. Our objective was to verify and expand the previously reported results, which were somewhat tentative (12). Measurements in several new paper types are reported.

THEORY AND ANALYTICAL TOOLS

We wish to consider flow through an anisotropic disk of paper. Analysis of this flow problem begins with Darcy's law:

$$\mathbf{v} = \frac{-\mathbf{K} \cdot \nabla P}{\mu}, \tag{1}$$

where $\mathbf{v}$ is the superficial velocity vector, $\mathbf{K}$ is a second-order permeability tensor (a 3x3 matrix with only three independent terms [17]), μ is the viscosity, and ∇P is the pressure gradient. If a Cartesian coordinate system is chosen to correspond with the principal flow directions of the porous medium, then the permeability tensor becomes a diagonal matrix:

$$\mathbf{K} = \begin{bmatrix} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & K_z \end{bmatrix}, \tag{2}$$

where K_x, K_y, and K_z are the principal permeability components in the x-, y-, and z-directions, respectively, of the principal axis frame. In paper, these directions will generally correspond to the cross-direction (defined here as x), the machine-direction (y), and the transverse direction (z).

If all three components of the diagonal permeability tensor are identical, the medium is said to be isotropic. The $\mathbf{K}$ tensor can then be replaced by a scalar which multiplies the magnitude of the pressure gradient. In this case, the velocity vector and the pressure gradient vector will always have the same direction. In an anisotropic porous medium, however, the direction of flow need not be in the same direction as the pressure gradient.

The ratio of the y-component (MD) to the x-component (CD) is defined as α, the in-plane anisotropy ratio:

$$\alpha = \frac{K_y}{K_x} . \tag{3}$$

If the two components are identical (α=1), the medium is said to be isotropic in the plane. In-plane isotropy is expected in handsheets, but not in machine-made papers where fibers are oriented preferentially in the machine direction. The ratio of average lateral or radial permeability, K_r, to the transverse permeability is defined here as β, the normal anisotropy ratio:

$$\beta = \frac{(K_x + K_y)}{2\,K_z} = \frac{K_r}{K_z} . \tag{4}$$

To obtain estimates of permeability components from flow through an anisotropic sample, Darcy's law must be combined with the equation of continuity. For the flow of a single incompressible liquid through a saturated porous medium, the continuity equation is simply

$$\nabla \cdot \mathbf{v} = 0 \quad . \tag{5}$$

Combining this with Equation 1, we obtain

$$\nabla \cdot \mathbf{K} \cdot \nabla P = 0 . \tag{6}$$

Equation 6 must be solved with the boundary conditions for the flow problem of interest. While exact analytical solutions may be impossible to obtain, approximate solutions can be used with high accuracy in some cases. Solutions for the flow problems of this study are given below.

EXPERIMENTAL APPROACH

Lateral Permeability

Apparatus

Figure 1 is a photograph of the apparatus used in this study for lateral permeability measurements. The key components are shown schematically in Figure 2. The apparatus was assembled as part of a graduate project undertaken by Wallin at IPST (18). A Carver press was modified to hold two heads which would press paper between two steel platens. The original manual hydraulic jack of the Carver press was replaced with a Firestone Airide™ air bag assembly, capable of providing loads up to about 18 kN (4000 lb). A pneumatic operating system was installed to control the air bags. The upper head, which is driven by the air bags, is

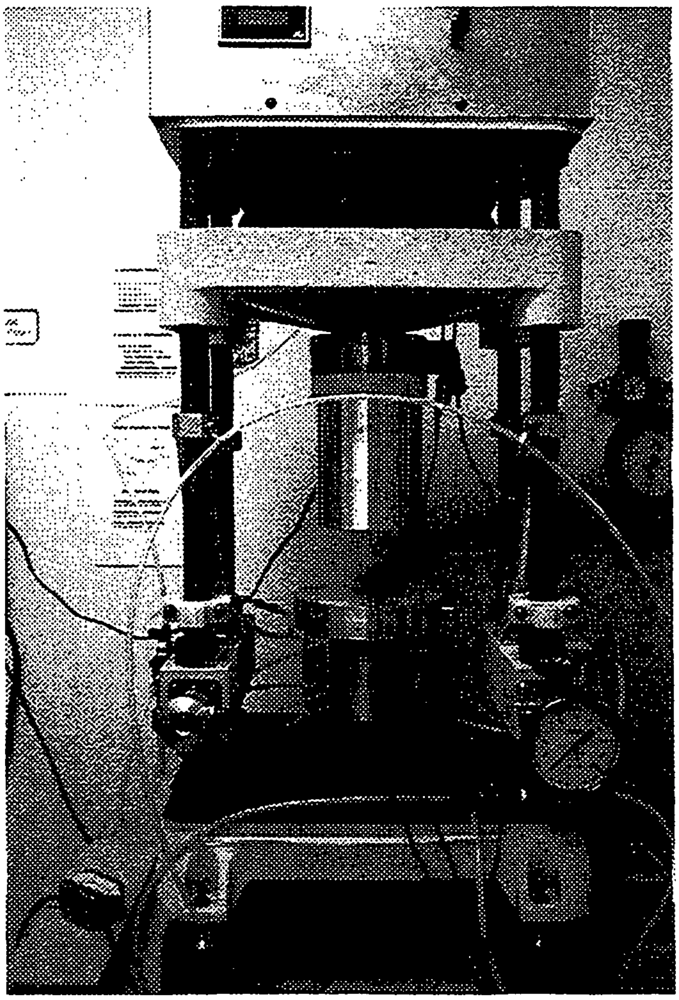

Figure 1. Permeability apparatus facility arranged for lateral permeability measurements.

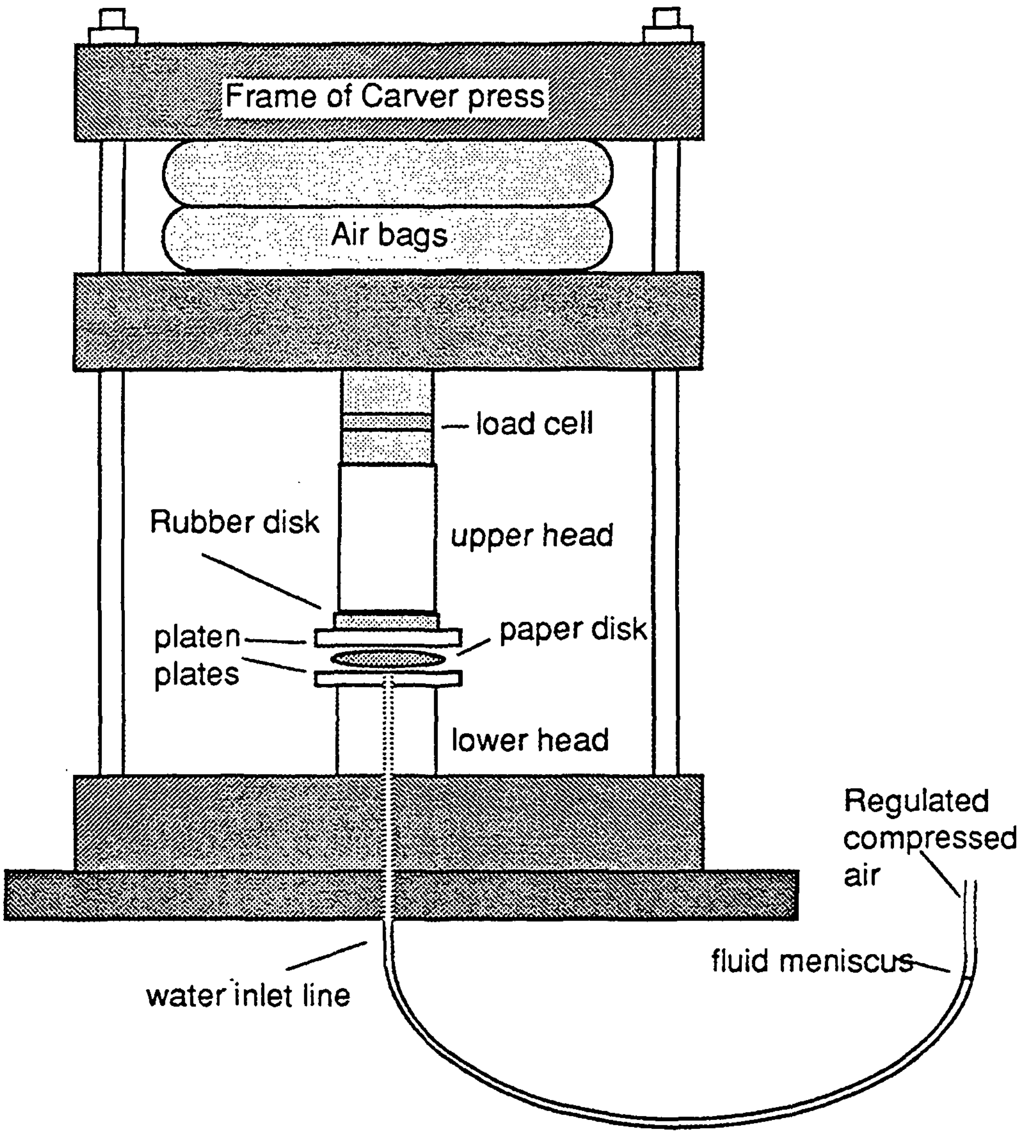

Figure 2. Schematic of the lateral permeability setup.

a solid cylinder of aluminum, 0.13 m in diameter. A rubber disk is placed between the upper head and the upper platen to help provide uniform loads. The lower head is a thick-walled hollow cylinder through which plastic tubing can pass. The lower platen fits onto the lower head and has a fitting onto which plastic tubing can be connected. Fluid from the tubing can then pass to the upper surface of the platen, where an 0.56-cm circular injection port (simply a round hole) is located. Fluid is driven into the injection port by regulated compressed air above the fluid meniscus in the line, as shown in Figure 2.

After a paper disk is placed between the two platens, load is applied to provide a seal between the paper surfaces and the platens. Fluid in the tubing line is then pneumatically driven into the paper. The fluid flowing into the injection port enters the paper and is forced to flow radially outward through the paper itself. If the applied load is uniform, and the sheet itself is uniform in thickness, then channel flow between the sheet and the platens is avoided. This was verified by observing the location of dyed fluid injected into sheets. The observed dye boundaries showed the expected axes of symmetry (the shape was ellipsoidal, aligned with the MD and CD axes) and was not affected by rotation of the paper disk with respect to the apparatus. (With small applied pressures, say less than 0.15 MPa [20 psi], channeling might occur.)

Thickness Measurement

The thickness of the paper disk during lateral permeability measurements was measured with a set of linear variable displacement transducers (LVDT's). Three ST050 LVDT's from Schlumberger Industries were acquired, with an OD3 signal conditioner. The LVDT cores were embedded at 120° intervals around the edge of the lower platen, with sensor armatures mounted on the upper platen. The armatures induced an electronic signal in the cores, depending on the depth of penetration of the armatures. The output from the signal conditioner is read as milliamps on a digital multimeter. The difference between the response when the two platens are pressed together and when there is a disk of paper between them is related to the sheet thickness. Calibration of each core was done using an armature mounted on a micrometer in a plastic assembly. The size of the armatures installed on the upper platen was not matched carefully to the needs of this experiment, and as a result the LVDT's were typically operated in the nonlinear range, requiring a quadratic or cubic fit of the calibration data instead of the usual linear fit. This posed no serious problems, however.

Lateral thickness measurements were subject to a subtle error due to the response of the LVDT's. The presence of the metal mass of the upper platen connected to the armatures induced a signal change not accounted for in the calibration. Each LVDT responded differently depending on the offset of the sensor (each was embedded in the lower platen at a slightly different depth) and the thickness of the sample separating the sensor from the upper platen. A correction factor was obtained for the average of the three LVDT measurements, and the correction is expressed as a function of apparent average thickness. The correction correlation was obtained using 24 sets of LVDT thickness measurements of rigid brass and plastic sheets with known thicknesses of 5 to 80 mils (127 to 2030 μm). The correction factor as a function of apparent thickness was fit to a quadratic equation with an adjusted R^2 of 0.976. The accuracy of the correction factor was confirmed in further thickness checks during a series of measurements on a different day. The accuracy of thickness measurements in lateral permeability measurements is estimated at ±6 μm (±0.25 mils), an error which is much greater than the inherent resolution of the LVDT's. The error is primarily due to uncertainties in the true thickness of calibration materials (mostly brass disks of shim stock) under compression. Improved calibration procedures may substantially reduce this error, although it is adequate for this study and is an improvement in accuracy over previous results, where the uncertainty was probably about 10-15 μm.

Data Reduction

For radially outward flow in a saturated disk of paper, Equation 6 can be solved easily if $K_x = K_y$, which should be true in handsheets. The lateral permeability is expressed in terms of easily measured parameters:

$$K_r \equiv \frac{K_x + K_y}{2} = \frac{Q\,\mu \ln(R_o/R_i)}{2\pi\, L\, \Delta P}, \tag{7}$$

where Q is the volumetric flow rate, R_o is the outer radius of the sheet, R_i is the radius of the injection port, L is the sheet thickness, and ΔP is the pressure drop from the injection port to the edge of the sheet (the gauge pressure of the fluid in the tubing). Step-by-step details of this solution are given for a related problem in the appendix of Horstmann et al. (15). Numerical analysis has indicated that Equation 7 can be applied with reasonable accuracy even when $K_x \neq K_y$ (9).

Sheet porosity, ε, is obtained using the measured sheet thickness and the assumption that all solids in the sheet have the same density as pure cellulose:

$$\varepsilon = 1 - \frac{m}{A\,L\,\rho_c}, \qquad (8)$$

where m is the oven-dry mass of the sheet, A is the planar area, and ρ_c is the density of cellulose, 1,550 kg/m^3. This should be an accurate assumption for the sheets used in this study, and any errors in this assumption will affect both the lateral and transverse permeability-porosity relationships in the same way. Estimates of β, the ratio of lateral to transverse permeability, will thus be unaffected by the assumption of pure cellulose solids in Equation 8.

Transverse Permeability

Apparatus

The equipment used to measure transverse permeability also uses the Carver press and is shown in Figure 3. A schematic of the water flow and collection system is shown in Figure 4. This equipment is similar to that used in the previous part of this study with an electrohydraulic press (12), although key parameters (hydraulic head, injection pressure, and sheet thickness) are now measured and controlled with better accuracy. A paper disk, 0.076 m (3 inches) in diameter, is compressed between two felts. The felts are in contact with finely drilled bronze plates, which provide mechanical load while allowing water to flow through. The bronze plates are drilled with 0.0023-m (0.09-in) holes, with a center-to-center distance of 0.0032 m (0.125 in). The open surface area is 47%. The plates are thick enough (1 in or

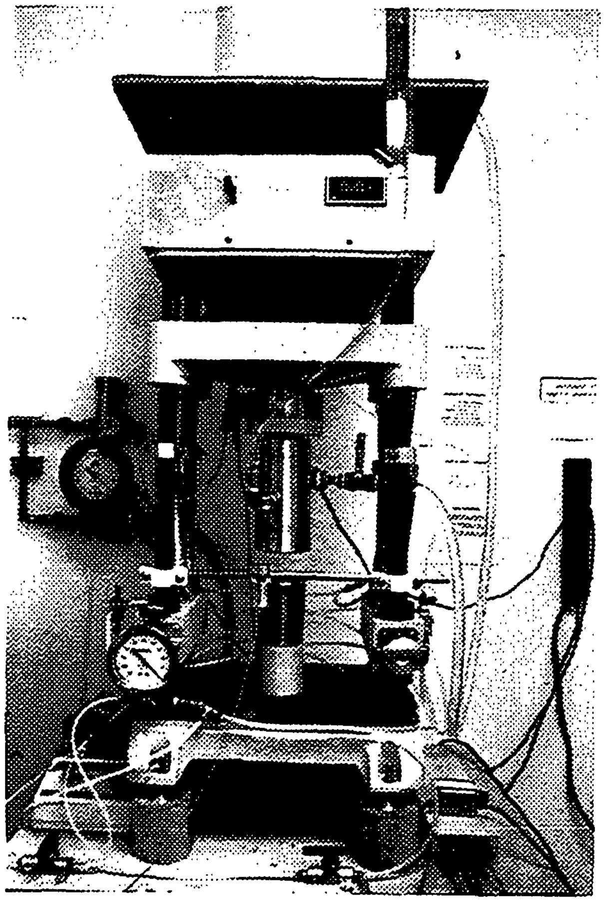

Figure 3. Photo of the transverse permeability setup.

0.0254 m) to prevent significant bowing during compression. The hydraulic head in the upper chamber is created by the height of a water reservoir above the Carver press; the reservoir is sufficiently wide to keep the hydraulic head nearly constant during a typical single measurement (if needed, additional water is added to the reservoir during a measurement). The hydraulic head, measured in centimeters above the location of the paper disk, is read from a marked column connected to the upper head. Frictional losses as water passes from the reservoir through a valve makes the measured head several centimeters of water less than the height of the reservoir surface above the paper.

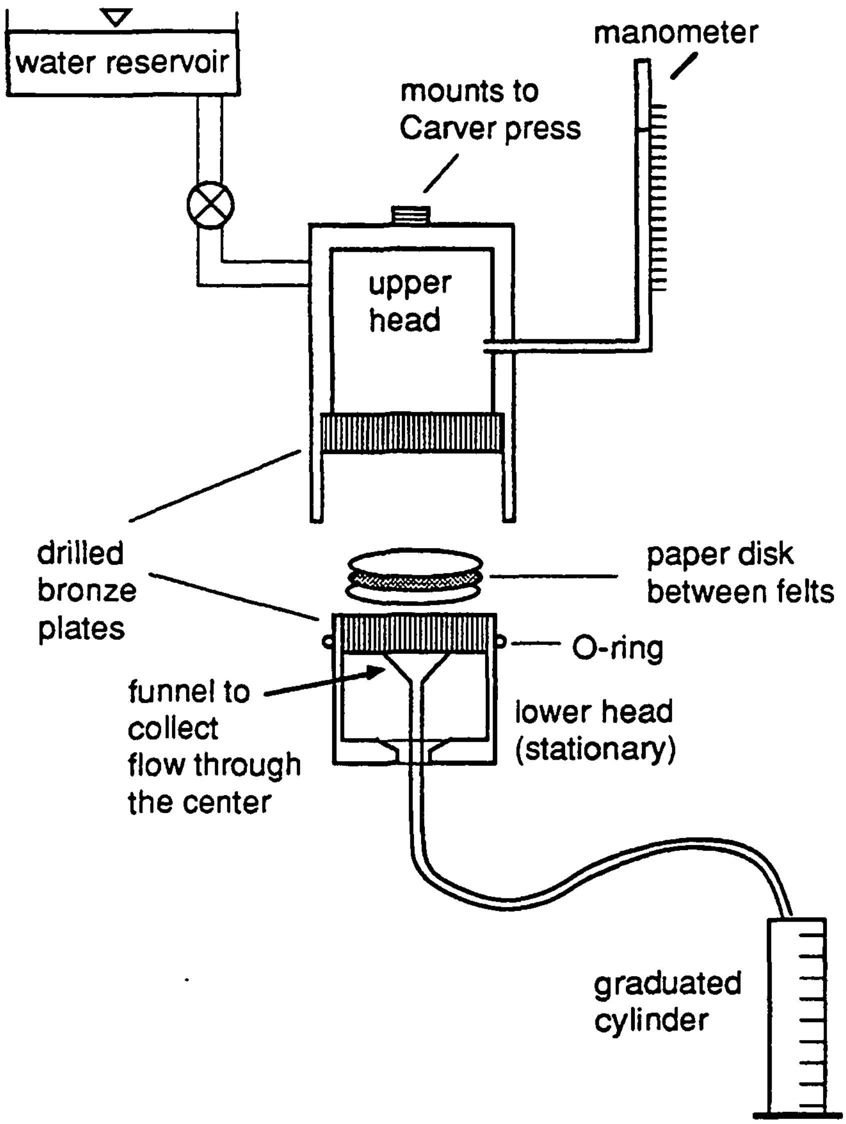

Figure 4. Schematic of the water flow system for transverse permeability measurements.

Fluid passing through the paper disk exits through the lower felt and the lower drilled bronze plate. The felts were necessary to provide uniform mechanical pressure and uniform hydraulic boundary conditions. Carbon paper imprints taken under load confirmed that the felts were adequate in generating a uniform load across the paper.

To eliminate problems with leakage around the edge of the paper, only the flow through the central region (comprising 23% of the area of the paper disk) was collected and measured. This fluid entered a funnel which led the fluid through plastic tubing to a graduated cylinder below the Carver press assembly. Flow collection times ranged from 30 seconds to over an hour, and were measured with a stopwatch. When an impermeable plastic disk was placed between the felts, leakage around the edges of the plastic and felt disks allowed water to pass through to the lower chamber, but there was no flow through the central region where measurements were made, indicating that use of flow from the central region only succeeded in eliminating edge effects. However, sometimes lateral flows in the felts were detected which brought a small amount of water in from the edge (this problem was not easily reproduced and was often puzzling). This problem was overcome or greatly reduced by flame-sealing the edge of the felts, and by cutting a thin groove near the outer edge of the felts to interrupt lateral flow, allowing it to drop freely into the holes of the bronze plate. Since these treated felts gave essentially the same results as similar untreated felts, these precautions may have been unnecessary. The point, however, is that efforts were made to eliminate errors due to edge effects and lateral flows in the felts. Any edge effects that did occur had a negligible effect on the results of this study.

Thickness Measurement

The position of the upper head in the Carver press was measured with a Kaman eddy-current transducer (ECT), which has the potential for accuracies better than ± 0.1 μm. The transducer was connected to a stationary bar across the Carver press frame, and measured the distance to an aluminum target mounted on the pipe to the water column coming from the upper head. By measuring the position of the upper head while compressing two felts alone and then while compressing the two felts plus paper, the thickness of the sheet could be obtained from the difference.

Several factors had to be dealt with to obtain accuracy in this procedure. First, the ECT had to be calibrated and adjusted daily to ensure proper linear response. Second, before and after each transverse permeability run, the thickness of the two wet felts together had to be determined as a function of applied mechanical load. Cubic regression of the thickness-versus-load data was done for the felts before and after the permeability run in case long-term deformation of the felts had occurred. The "before" and "after" regression equations (adjusted R^2 typically > 0.99) were then averaged and used to predict what the felt thickness alone was during runs with paper present. The difference in the measured thickness and the calibrated felt thickness at that load gave the apparent paper thickness.

The accuracy of this procedure was checked by using disks of metal stock of known thickness instead of paper. A consistent error of $+2x10^{-5}$ m (0.8 mils) was detected, which was apparently due to a felt interface effect. Because the open fabric of the felts can intermesh when compressed together, two compressed felts together have a smaller thickness than would be obtained with a rigid plane of zero thickness separating the felts. Thus in checking the EDT by putting in rigid materials of known thickness, the measured values were all too thick by about 0.8 mills. This correction factor was then incorporated and confirmed in subsequent calibration work.

Using the corrected procedure for obtaining the paper thickness between the compressed felts, the final accuracy of the thickness measurement is estimated to be $\pm$ 9 µm (0.35 mils). Given the inherent uncertainties in defining paper thickness, this error is fairly small.

The current thickness measurement technique is an improvement over what was done in the earlier phase of this study, where a relatively crude mechanical displacement meter was used.

Data Reduction

In the case of transverse permeability measurements, water passes straight through the central region of the paper and felts with a known pressure drop. The transverse permeability is given by:

$$K_z = \frac{L}{\dfrac{A_{flow}\,\Delta P}{Q\,\mu} - R_f}\,, \tag{9}$$

where A_{flow} is the cross-sectional area of the flow collection region (23% of the sheet area) and R_f is the inherent resistance of the felts and flow system. The flow resistance of the drilled plates and felts alone was measured several times in order to obtain a value for R_f. It was only a weak function of felt compression, and was treated as a constant in Equation 9. For most runs, R_f was of little importance since the paper resistance was so much greater.

RESULTS

Much of the work of this portion of the study was devoted to developing the proper experimental techniques for the new equipment. Once reproducible results could be obtained, measurements were first made in sheets produced from a Southern softwood unbleached kraft (SSK) pulp. This furnish, used to produce linerboard, had a freeness of about 700 CSF. Lateral and transverse permeability measurements were made in a single 0.076-m (3-in) disk cut from a handsheet. Results are shown in Figure 5. The value of β in this sample ranges from about 2 to 4 over the porosity range shown. These results can be compared with previous data from linerboard handsheets made with another SSK pulp (12), reproduced in Figure 6. The previous measurements gave β values of about 1.5 to 2. They were subject to a number of possible errors, but are still consistent with the new measurements using a different pulp. However, the new data show that β increases with porosity, while previous measurements in linerboard gave the opposite trend.

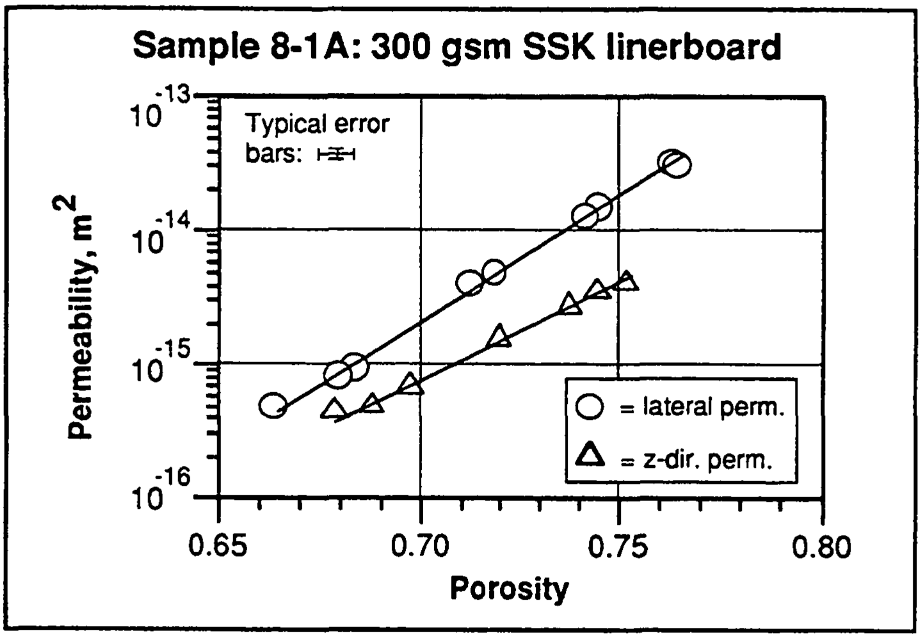

Figure 5. Lateral and transverse permeability in a linerboard handsheet.

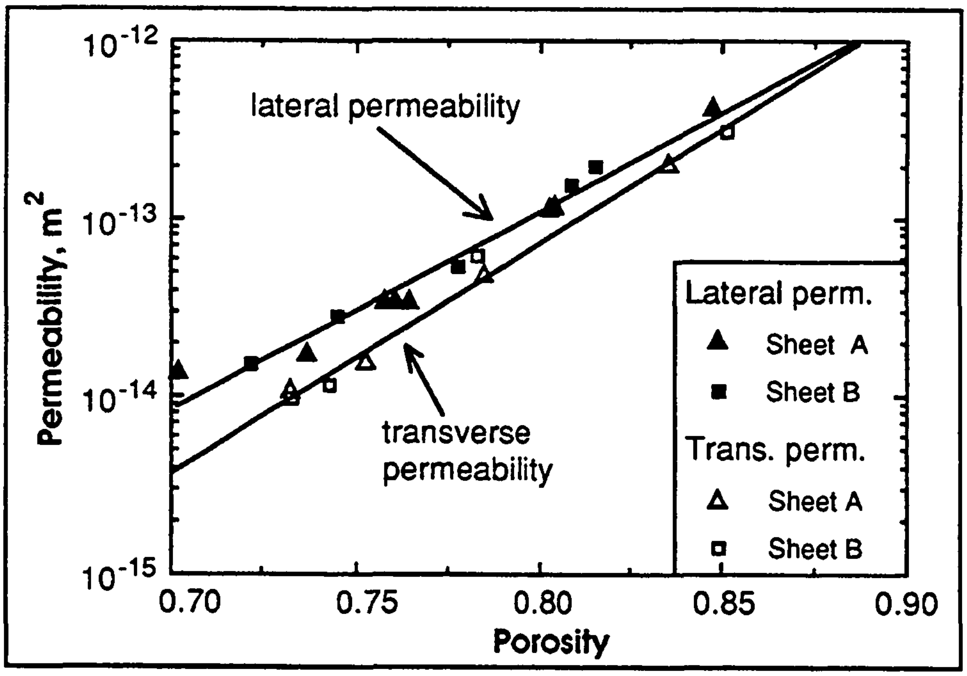

Figure 6. Previously published results for lateral and transverse permeabilities in linerboard handsheets from another SSK furnish (12).

In examining the reproducibility of permeability measurements in linerboard sheets, two clusters of data arose, depending on the history of the handsheet. Some handsheets had been made with the newly obtained fresh pulp for use in early trials with the present equipment, as described in Wallin (18). In addition, some couch trim had been taken from a commercial linerboard machine running the SSK furnish. Sheets from this early part of the current study were stored under refrigeration and measurements were made in them several weeks later, once the experimental techniques had been fully developed. In addition, new handsheets were then made from the pulp slurry which had also been stored under refrigeration. Interestingly, the sheets from the stored pulp had lower permeabilities than the handsheets and couch trim which came from the fresh pulp and were then stored. The difference in permeability is shown by transverse permeability data in Figure 7.

Physical changes in the pulp slurry may have occurred, even though the freeness did not change significantly. On the other hand, the pulp was washed and screened and handsheets were formed by a different person for the two cases, and the difference may be partially due to a difference in fines level or handsheet formation technique. Fiber analysis has been planned to better understand why the two sets of samples are so different.

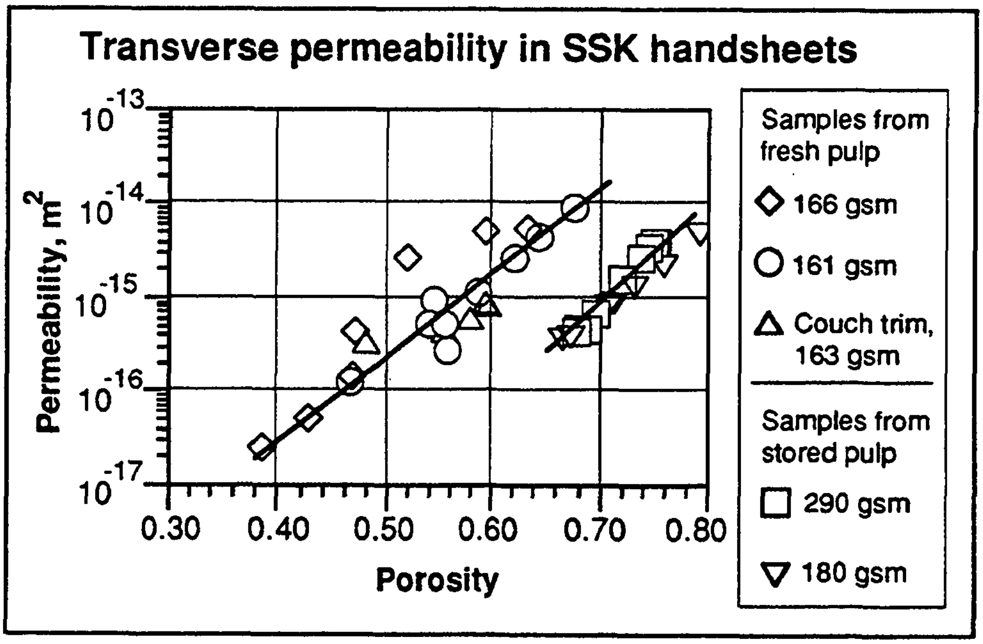

Figure 7. Comparison of transverse permeability measurements in two sets of samples from SSK linerboard pulp.

In the lower permeability line in Figure 7, two basis weights give the same permeability results. This held true in other samples examined in this study. Ideally, permeability should be independent of basis weight in a uniform, homogeneous porous medium. In very thin sheets, however, nonuniformities may lead to channels in the z-direction or in the plane, which may lead to apparent differences in permeability. The increased difficulty in defining a sheet thickness in very thin sheets would also affect the measurements of permeability as a function of porosity.

Measurements were also made in an unbleached thermomechanical pulp (TMP) with a freeness of about 100 CSF. Lateral and transverse permeability results are shown in Figure 8, where separate data for two 200 gsm handsheets are included. The reproducibility of the measurement techniques appears satisfactory. Note, however, that large differences between the lateral and transverse permeability values exist. Values of β range from about 5 at low porosities to nearly 10 at the higher porosities measured. This is larger than the range reported in the previous study, where the highest β values seen were about 4-5 (12).

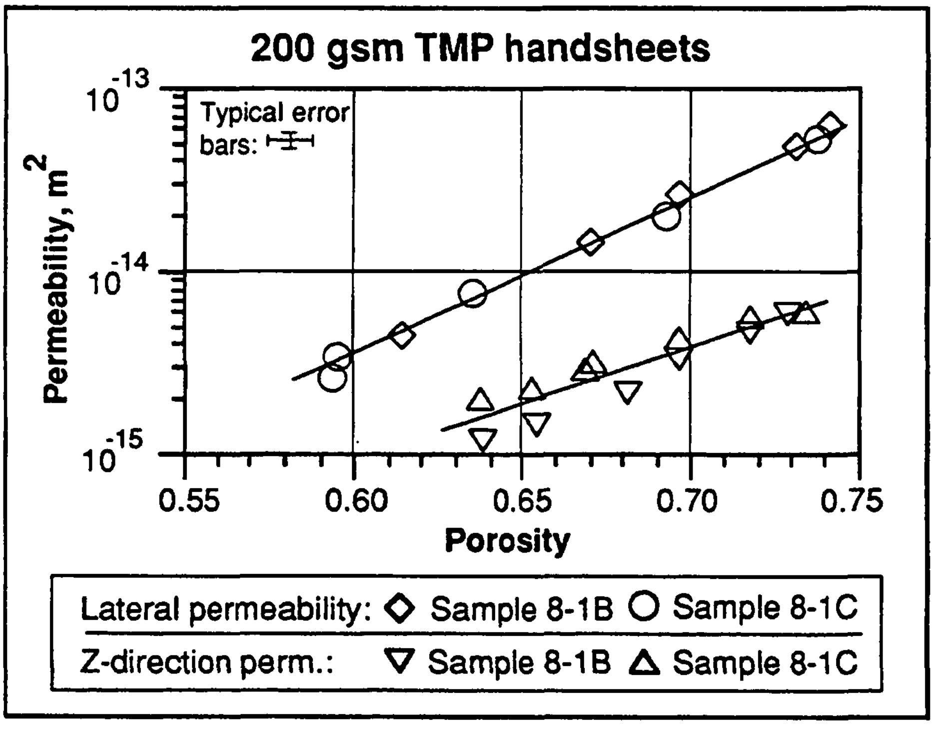

Figure 8. Lateral and transverse permeabilities in two 200-gsm TMP handsheets.

Further lateral and transverse permeability measurements with TMP are shown in Figure 9, where an 87 gsm handsheet was used. Transverse permeability measurements were repeated using a different set of felts and a different operator (a lab technician) as a check on the experimental method. The agreement between the two runs is excellent, and the deviation at the lower porosity can be explained by a minor error in the felt thickness calibration procedure used during the second run. In these samples β is virtually constant over the porosity range examined, with a value near 10.

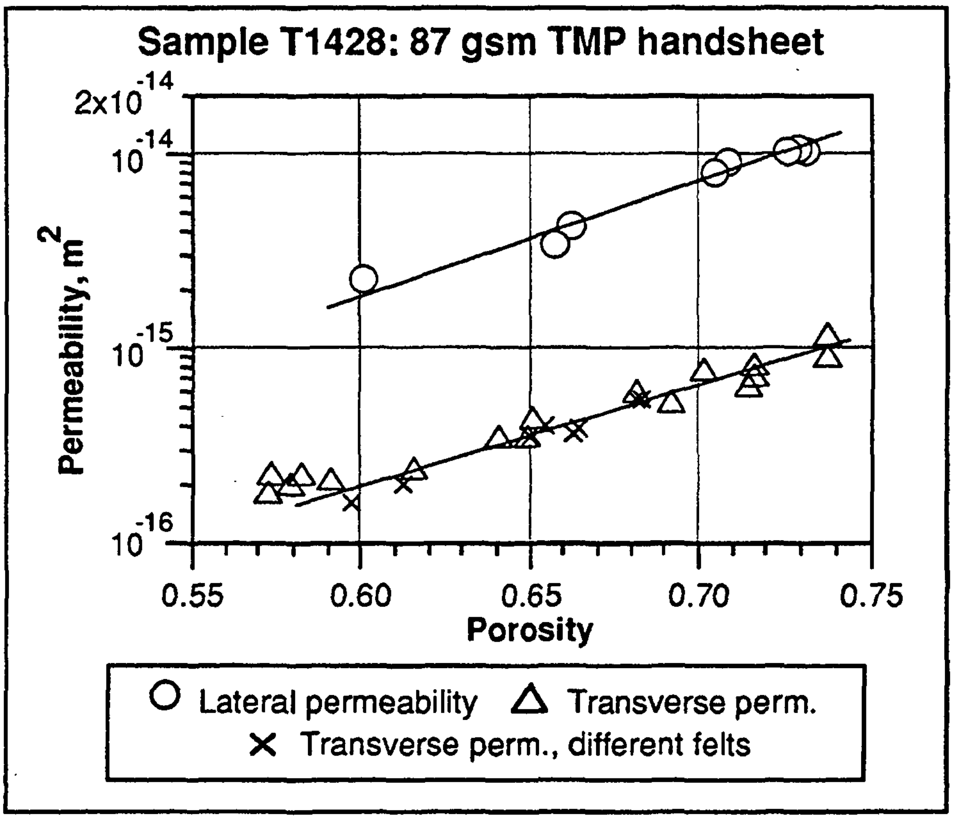

Figure 9. Lateral and transverse permeability measurements in an 87 gsm TMP handsheet.

As with the linerboard sample, two clusters of permeability data were found in the TMP samples. This is shown in Figure 10. (Similar clusters appeared in the lateral permeability data curves). Sheets from one batch, all prepared during one week by one of the authors, had a lower permeability than sheets prepared from the same pulp but made several weeks later by a laboratory technician. Perhaps the washing and screening done for the second batch removed more fines from the pulp and increased the permeability. These results are still perplexing since just the opposite trend was seen in the linerboard, where the handsheets made by a technician from the stored pulp had lower permeabilities. In this case, however, the pulp was not fresh for either set of data, but had been in storage at IPST for about one year. Physical degradation of the pulp over time may thus account for the changes in permeability shown in Figure 7, while washing of fines from already stabilized pulp may explain the changes in Figure 10. Again, fiber and sheet analysis is needed to elucidate these phenomena.

The results in Figure 10 also show that the measured transverse permeability was not a function of sheet thickness for the range of basis weights examined.

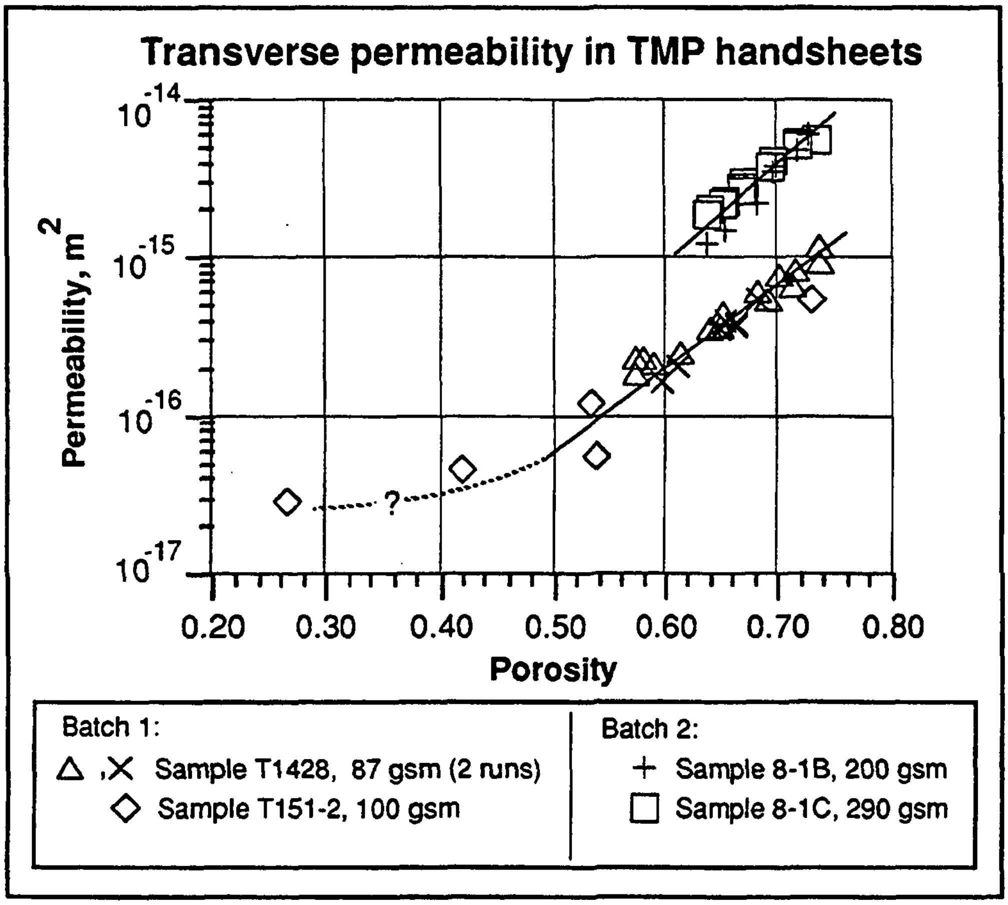

Figure 10. Comparison of transverse permeability measurements in two batches of TMP sheets prepared at different times and by different people.

Several other sets of either lateral or transverse permeability data alone were collected, but are not included here. Lateral permeability measurements were also attempted in the couch trim from a linerboard machine, but the uniformity of the couch trim was very poor (50% variation in thickness across the width of a sample), resulting in measurements that were impossible to interpret. (Transverse permeability measurements in couch trim could be made with more confidence because a smaller cross-section of uniform thickness is needed in those measurements.)

DISCUSSION

Where an accurate comparison of lateral and transverse permeabilities in a single sheet was possible, β values greater than 1 have again been found in this study, confirming the findings of Lindsay (12). While Lindsay observed β values no greater than 5, and generally between 2 and 4, values as high as 10 have now been found. We must first consider whether such findings are physically plausible, and, if so, what implications there might be for the paper industry.

Previous authors have considered the flow of liquid over oriented arrays of cylinders, and concluded that the resistance for flow normal to the cylinders would be roughly twice that of the resistance for parallel flow (13,14,19). If paper could be approximated by such a flow system, then z-direction flow would correspond to flow normal to the cylinders, and in-plane flow would represent a combination of normal and parallel flow, depending on the fiber orientation distribution. The ratio of lateral to transverse permeability (inverse of the resistance ratio) should then be less than 2 and greater than 1.

Closer approximations to paper may be possible if flattened elliptical rods are considered instead of cylindrical rods. Epstein and Masliyah (20) modeled flow normal to infinite elliptical rods and found that the permeability was a strong function of axis aspect ratio and orientation of the rod. Their results suggest that for rods of aspect ratio 5 with the minor axis aligned with the flow, the transverse permeability could be on the order of 60% less than would be predicted from the Happel model. Applying this result to paper, the expected upper limit for β in paper may be on the order of 3 instead of 2, depending on the shape and orientation of the fibers.

Brown (21) found analytical solutions for flow normal and parallel to infinitely long elliptical fibers. For axis aspect ratios of 3 or less, he found that the predictions of models based on cylindrical fibers were accurate. For aspect ratios above 5, however, β values much greater than 2 are possible, with a value of 8 predicted for an aspect ratio of about 10. Brown cites an unpublished study (22) indicating that wet wood fibers generally have aspect ratios less than 3.5, but upon drying the lumens collapse and the ratio can become as large as 10.

Based on Brown's work, therefore, the high β values observed here may be physically plausible. Note also that Adams (15) reported β values ranging from 2 to 5 in a Ph.D. thesis dealing with in-plane flow in textiles. These measurements were incidental to his study and only a few were made, but they do strengthen the claim of plausibility for β values well above 2 in paper.

If high β values do exist in paper, several ramifications arise. Attempts to understand the fundamentals of pressing through analysis or computational techniques must reckon with the high lateral permeabilities which have previously been overlooked. Issues such as crushing and the back flow of water away from the nip must be reconsidered in terms of the anisotropic flow properties of paper. Results from this study also have application to the fundamental fluid dynamics of blade coating, where high in-plane pressure gradients can exist in paper near the blade which will affect the penetration and flow of coating (23). The concept of high lateral permeability is also influencing thinking concerning the problem of delamination in impulse drying, where the lateral flow of steam in a nip may be part of the problem but also may be used to help provide novel solutions (24).

One further ramification of this study comes from the observation that significant changes in permeability could occur in handsheets from a given pulp, possibly depending on either the storage time of the pulp or the details of the washing, screening, and handsheet formation processes. This suggests that small changes in the furnish (refining, screening, fines, additives, etc.) or in the formation process may have strong effects on true sheet permeability, even though the measured freeness of the pulp may not change significantly. Occasional monitoring of web permeability, perhaps even in couch trim samples or broke, might be informative in understanding the behavior of a paper machine and the effects of parameters at the wet end.

CONCLUSION

We have further confirmed a prior, tentative observation that lateral or in-plane permeability in paper is greater than the transverse or z-direction permeability. Ratios as high as 10 were observed in this study. Combined with the previous results, we can now say that, to date, all observations of this ratio, β, lie in the range of 1.5 to 10. This observation appears to be physically plausible, although simple attempts to predict β using arrays of cylinders as a model for paper give values less than 2. The relation between lateral and transverse permeability needs to be considered in future work dealing with wet pressing, blade coating, and any other system where two-dimensional flow in paper may be important.

ACKNOWLEDGMENT

Thanks to Glenn Dunlap for technical support, and to Gerald Kloth and James Burns for assistance in equipment design. Portions of this work were used by J.R.W. as partial fulfillment of the requirements for the Master of Science degree at The Institute of Paper Science and Technology.

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